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High-Field Magnets R&D in France for an FCC-hh

E. Rochepault

With inputs from: CEA Colleagues
CERN colleagues
PSI and EPFL colleagues

2nd FCC-France Workshop / January 20-21 2021

Courtesy H. Felice, Nov 2019:

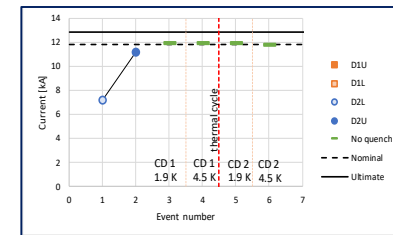
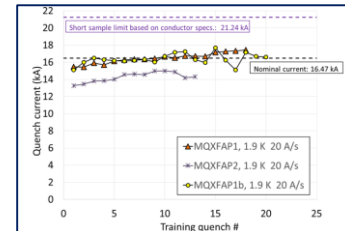
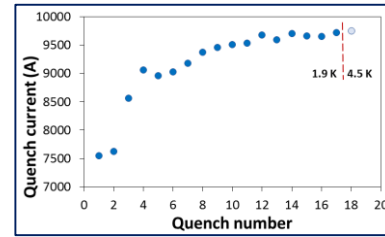
<https://indico.in2p3.fr/event/19693/contributions/76074/>

- Successful 16 T Nb₃Sn magnets without bore
- Encouraging 13-14+ T Nb₃Sn short models
- Successful 11+ T Nb₃Sn long dipoles and quadrupoles to be installed in HL-LHC

The community is working

- as an international team
- with a consistent development program

to tackle the remaining Nb₃Sn challenges



We are on a consistent path toward the 16 T frontier

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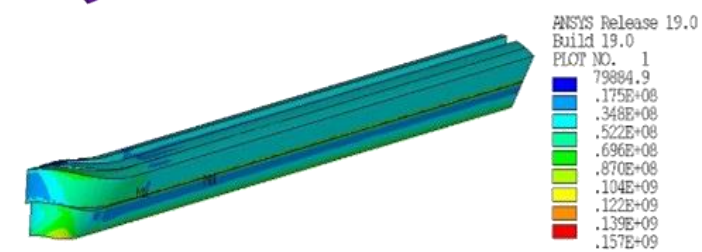
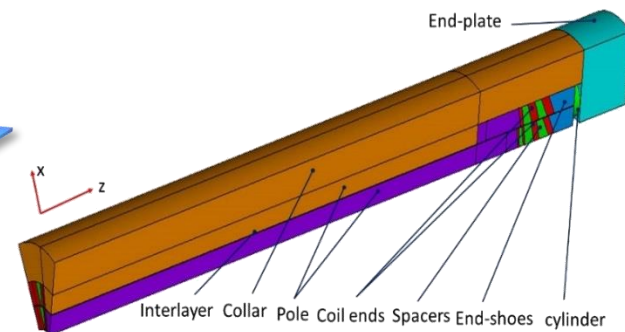
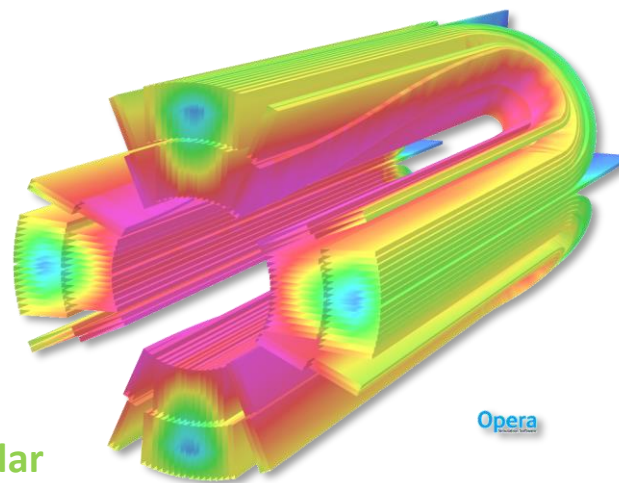
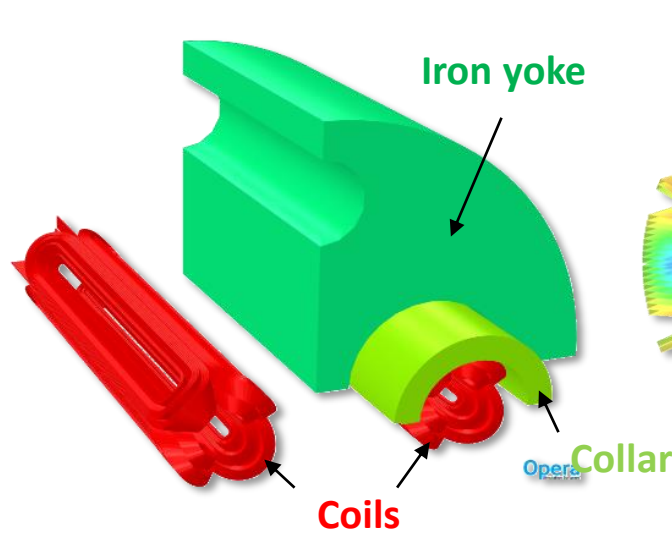
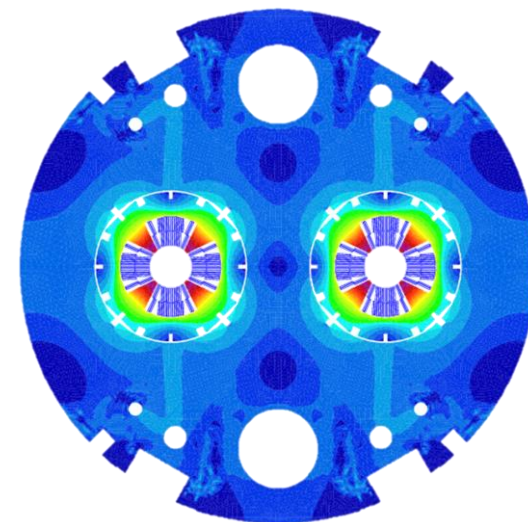
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MAGNET DESIGN AND STRATEGY

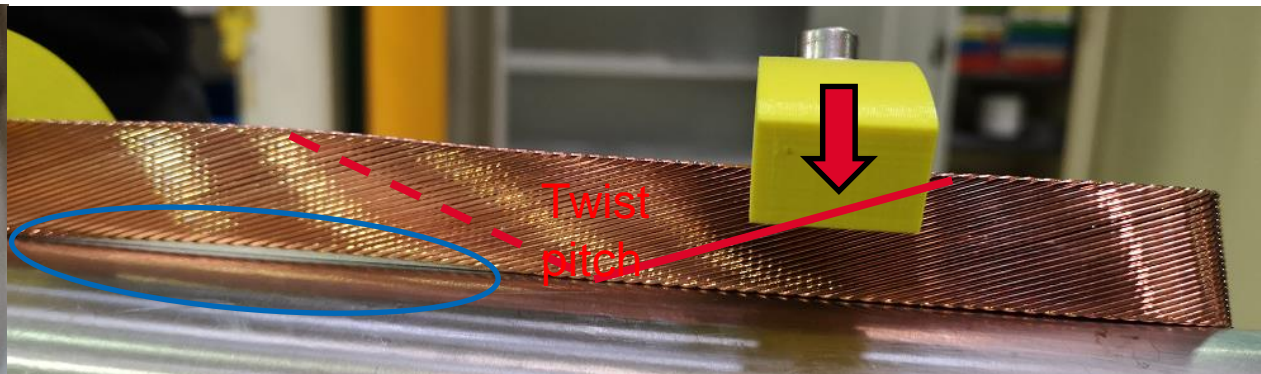
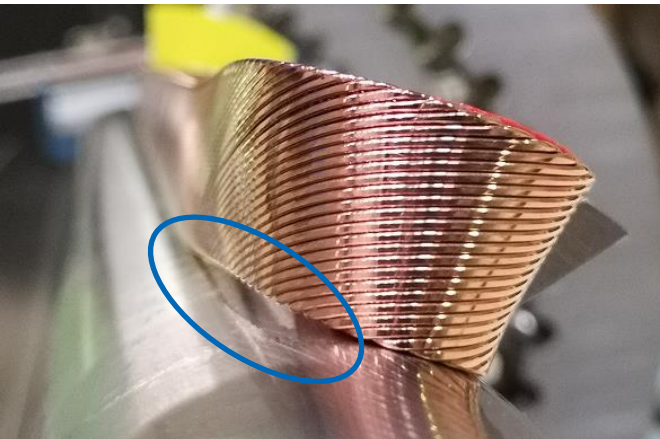
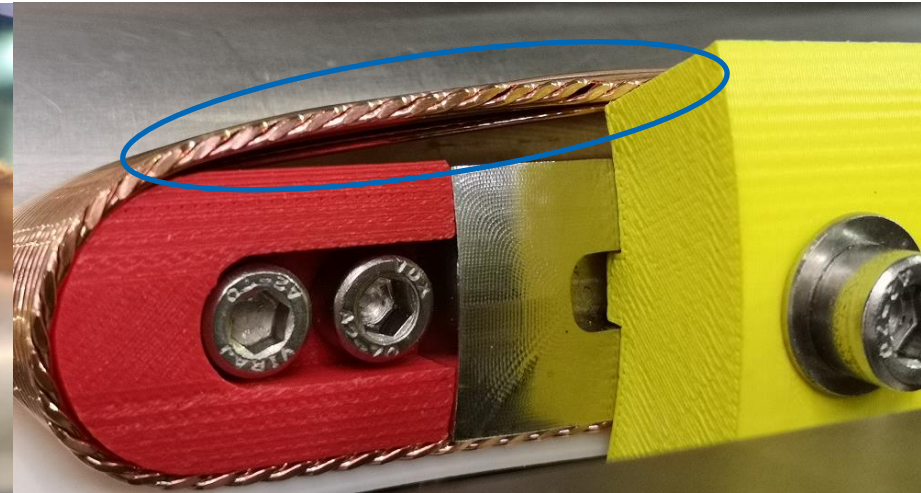
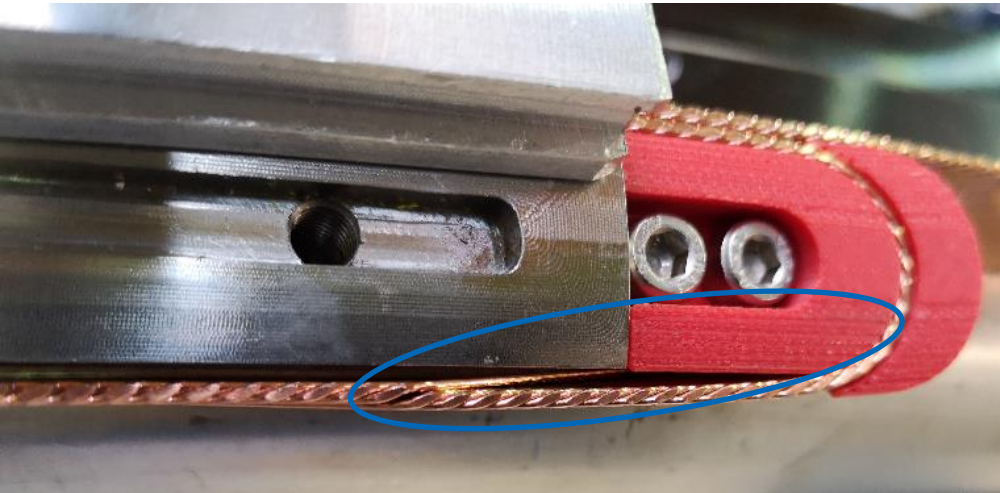
- 360 T/m double-aperture magnet, Nb₃Sn coils
- Conceptual design completed:
 - 2D/3D electromagnetic
 - 2D/3D mechanical
 - 2D protection (collaboration with TUT)
- Included in the final FCC CDR



Courtesy C. Lorin, C. Genot, C. Pes

2) Energisation

- Preliminary winding tests with actual cables
→ **Difficult winding** : requires future winding and cable R&D

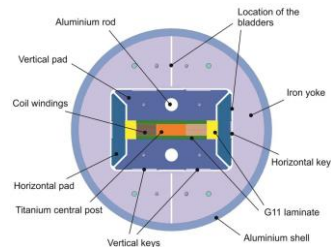


Courtesy C. Lorin, C. Genot

SMC Short Model

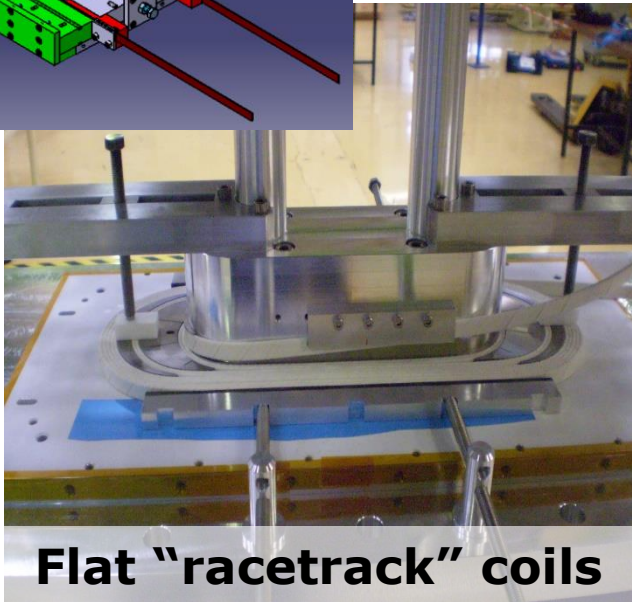
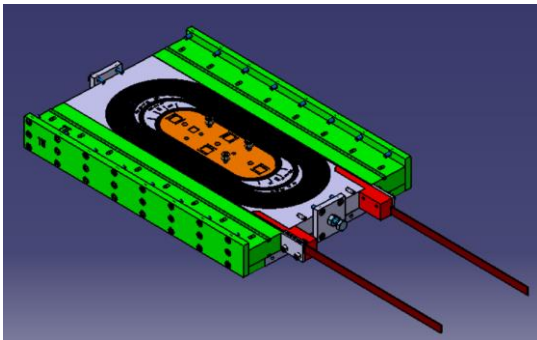
2021

Flat coils, 12 T



SMC = Short Model Coil

- CEA/CERN collaboration:
- Fabrication at CEA Paris-Saclay
- Assembly and tests at CERN
- **Goal: transfer coil fabrication technology from CERN to CEA**



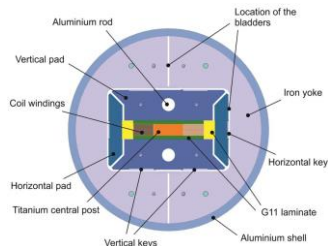
Flat "racetrack" coils



SMC Short Model

2021

Flat coils, 12 T

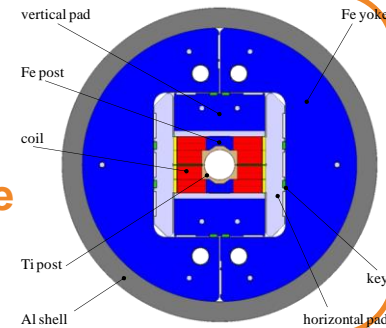


FRESCA2

2019

+Flared-ends + aperture

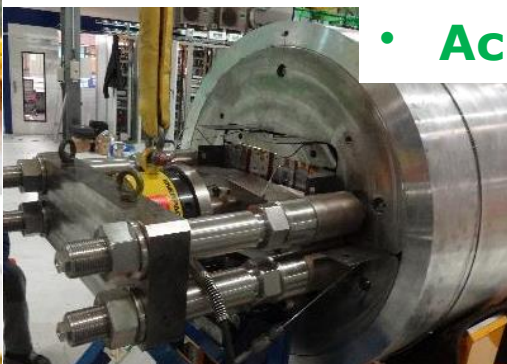
Current record of 14.6 T



Flared-end coils

FRESCA2 = Facility for REception of Superconducting Cables

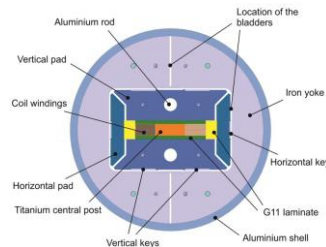
- CEA/CERN collaboration:
- Design and winding at CEA
- Fabrication, Assembly and tests at CERN
- **Achieved world record of 14.6 T**



SMC Short Model

2021

Flat coils, 12 T

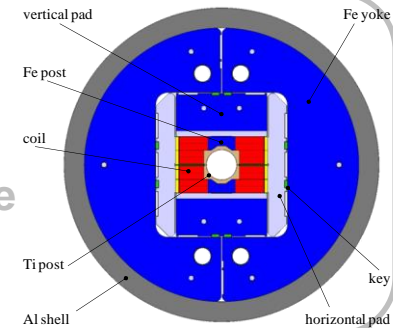


FRESCA2

2019

+Flared-ends + aperture

Current record of 14.6 T

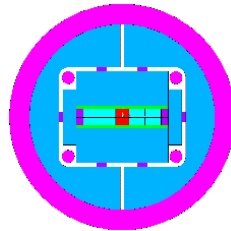


R2D2 Demonstrator

2023

Demonstrate **Grading**

→ 12 T



R2D2 = Research Racetrack Dipole Demonstrator

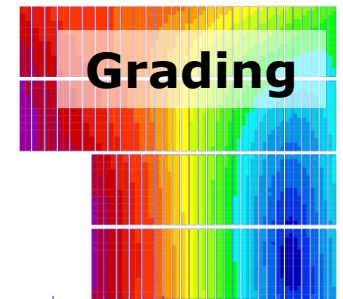
- CEA/CERN collaboration
- Fabrication and assembly at CEA
- Tests at CERN

• **Goal: demonstrate "grading"**

= 2 different cables in the same winding layer

→ Winding R&D + Junction R&D (see next slides)

→ **Conceptual design finalized¹**, detailed design ongoing



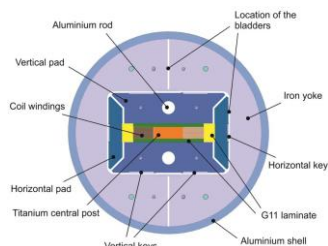
High Field "HF" cables Low Field "LF" cables

¹V. Calvelli et al., « R2D2, the CEA Graded Nb₃Sn Research Racetrack Dipole Demonstrator Magnet » submitted to IEEE TAS

SMC Short Model

2021

Flat coils, 12 T

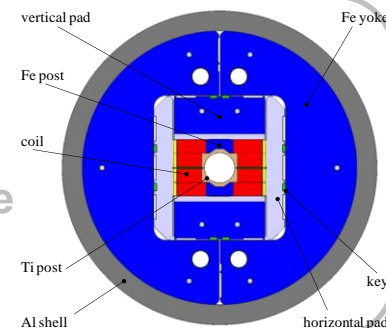


FRESCA2

2019

+Flared-ends + aperture

Current record of 14.6 T

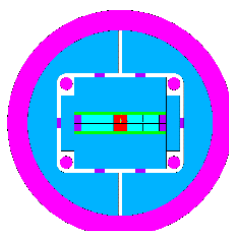


R2D2 Demonstrator

2023

Demonstrate Grading

→ 12 T

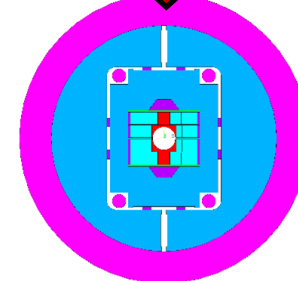


F2D2 Demonstrator

Future agreement

+Grading + Flared-ends

+ Aperture → 16 T

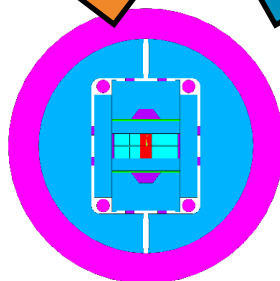


FD 'Reduced' demonstrator

Future agreement

+Grading + Flared-ends

→ 14 T



F2D2 = Fcc Flared-ends Dipole Demonstrator

- CEA/CERN collaboration under discussion

- **Conceptual Design Finalized**^{1,2}

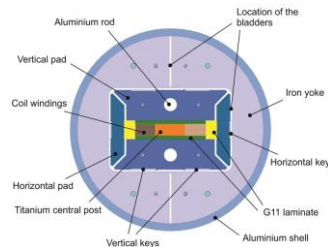
¹H. Felice, et al., "F2D2: A Block-Coil Short Model Dipole Towards FCC", IEEE TAS, 2019

²E. Rochepault et al., "3D Conceptual Design of F2D2, the FCC Block-Coil Short Model Dipole", IEEE TAS, 2020.

SMC Short Model

2021

Flat coils, 12 T

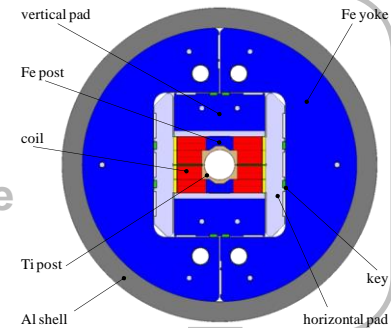


FRESCA2

2019

+Flared-ends + aperture

Current record of 14.6 T

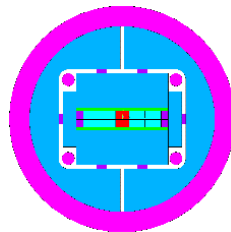


R2D2 Demonstrator

2023

Demonstrate Grading

→ 12 T

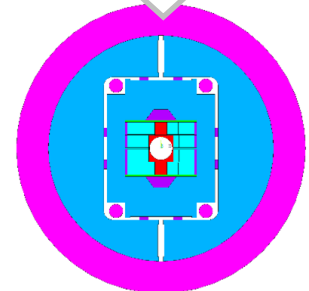


F2D2 Demonstrator

Future agreement

+Grading + Flared-ends

+ Aperture → 16 T

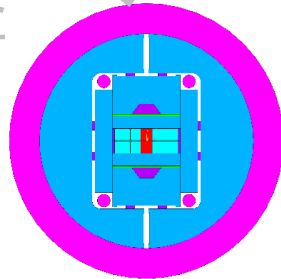


FD 'Reduced' demonstrator

Future agreement

+Grading + Flared-ends

→ 14 T

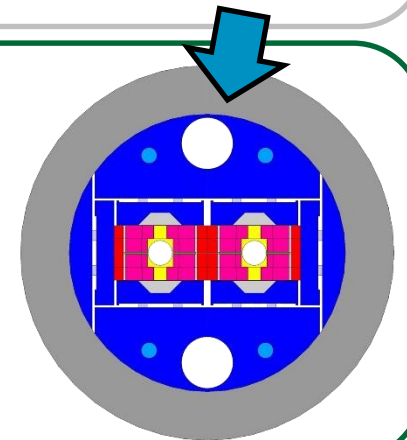


FCC Model¹

Far future

Double aperture

→ 16 T

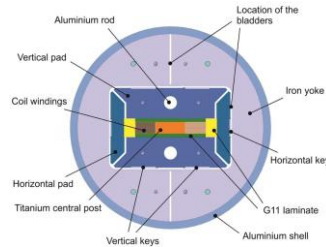


¹M. Segreti et al., "2D and 3D Design of the Block-coil Dipole Option for the Future Circular Collider" IEEE TAS, 2019

SMC Short Model

2021

Flat coils, 12 T

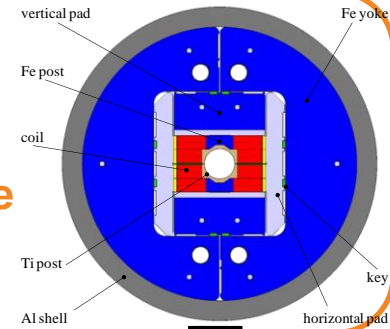


FRESCA2

2019

+Flared-ends + aperture

Current record of 14.6 T

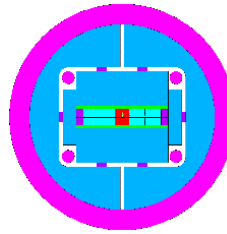


R2D2 Demonstrator

2023

Demonstrate Grading

→ 12 T

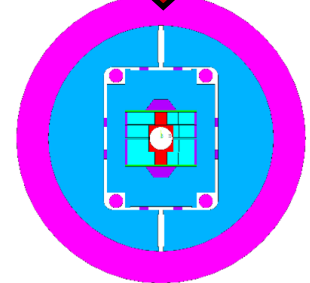


F2D2 Demonstrator

Future agreement

+Grading + Flared-ends

+ Aperture → 16 T

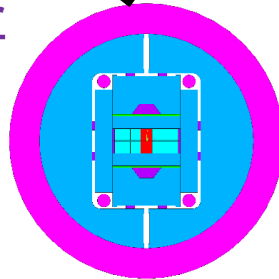


FD 'Reduced' demonstrator

Future agreement

+Grading + Flared-ends

→ 14 T

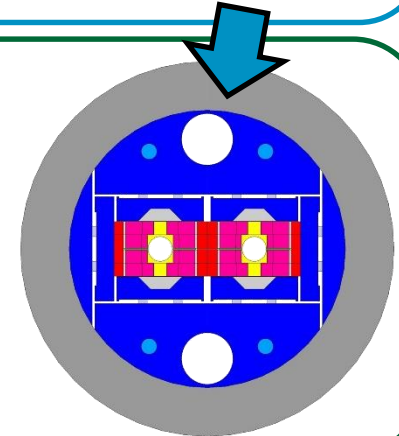


FCC Model

Far future

Double aperture

→ 16 T



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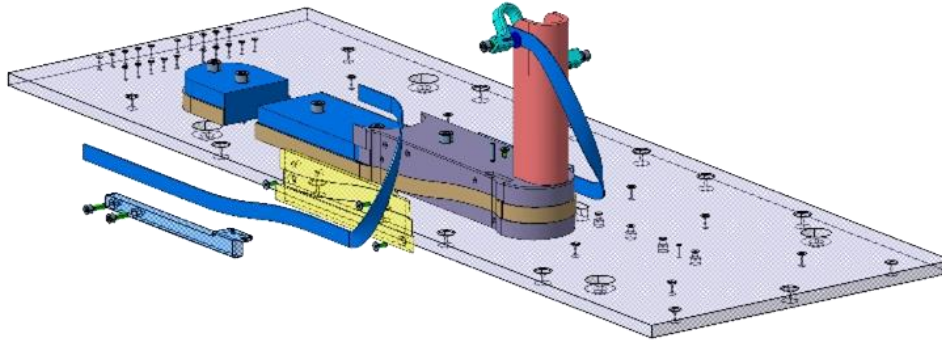
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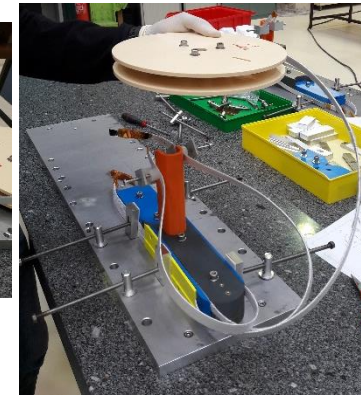
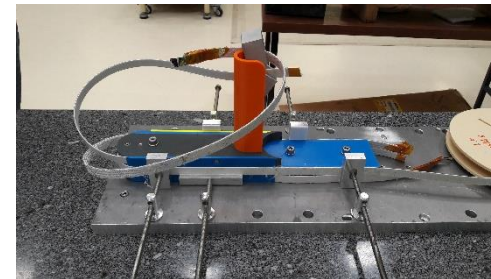
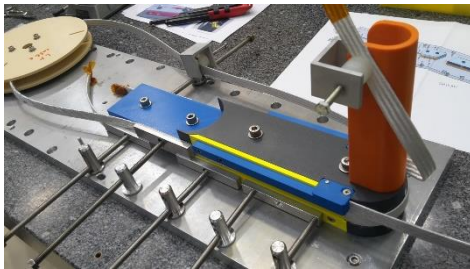
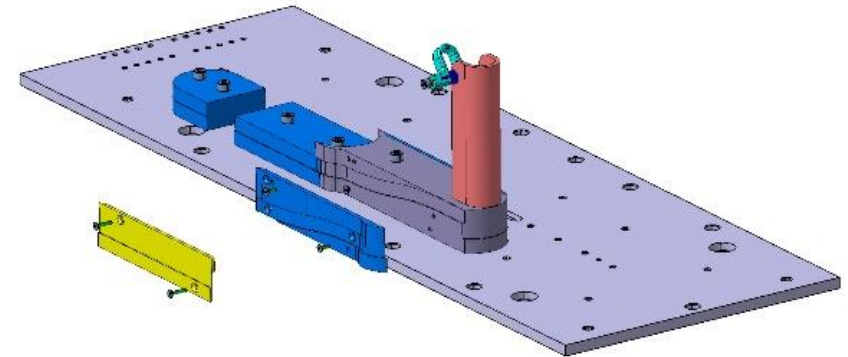
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PARALLEL R&D PROGRAMS

Mock-up A

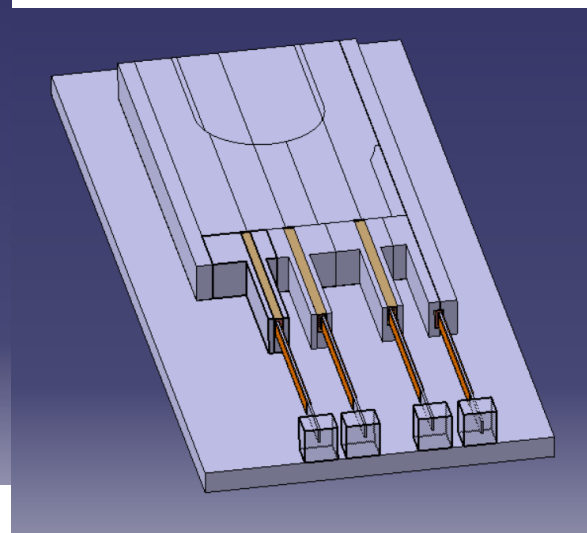
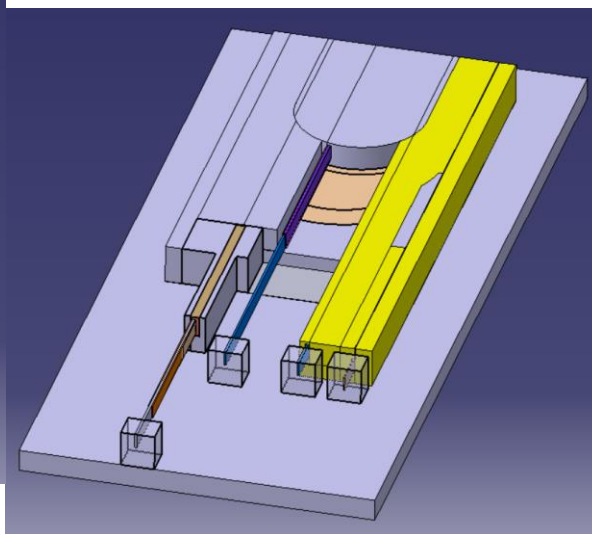
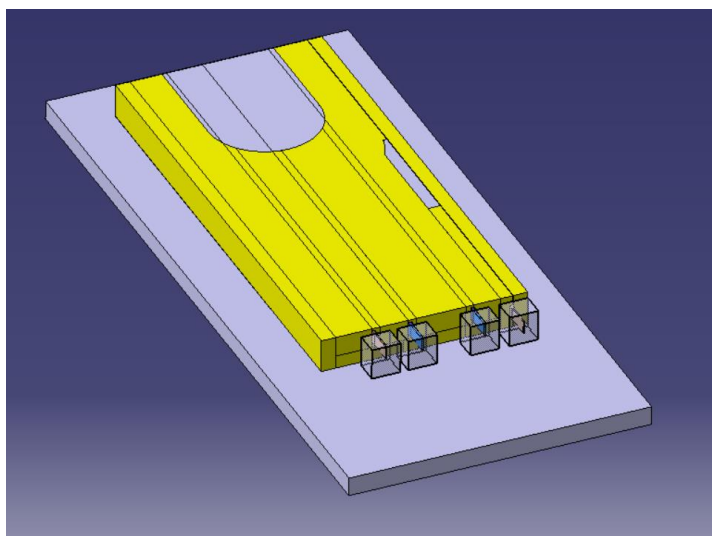


Mock-up B



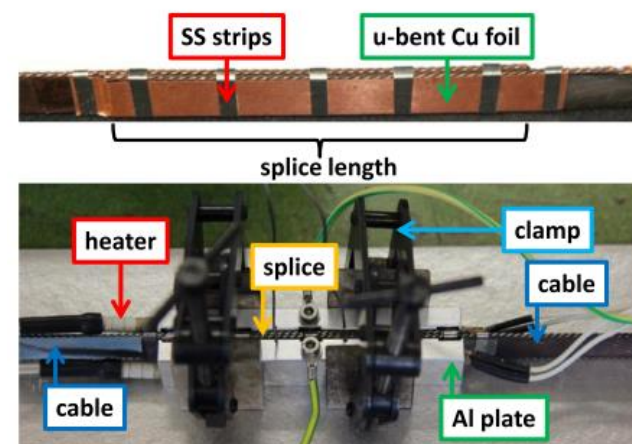
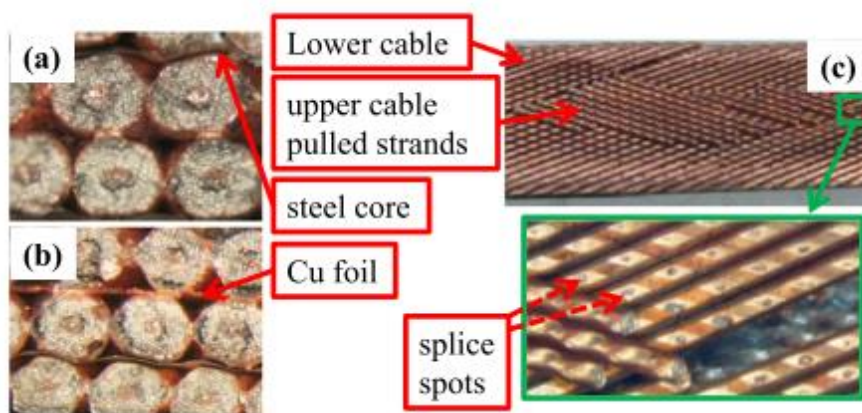
- CEA/CERN collaboration
- Mock-ups using actual cables + 3D-printed parts
- **Concepts validated for winding graded coils**

- CEA/CERN collaboration
- Mock-ups using actual cables + 3D-printed parts
- **Goal : validate concepts to perform external junctions**
- **Tests foreseen early 2021**
- **Feedback expected to finalize detailed design of R2D2**



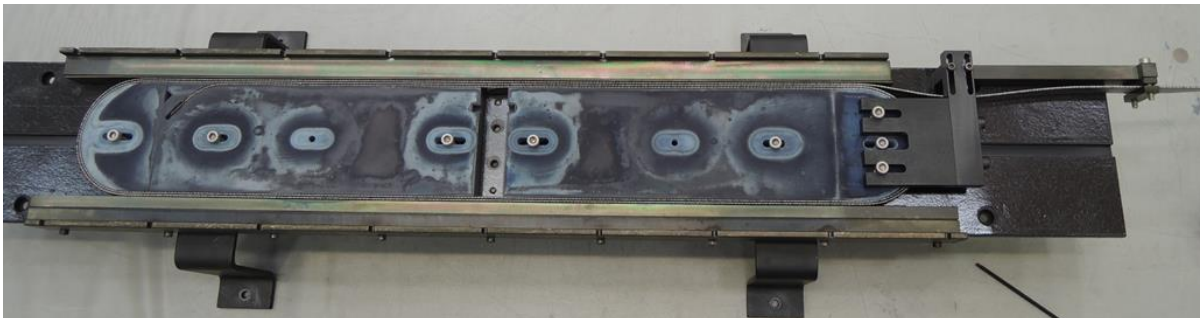
Courtesy M. Kumar

- EPFL-SPC/CERN/CEA collaboration
- Development of innovative methods for internal junctions¹
 - **Ultrasound welding → to be improved**
 - **Diffusion bonding → low resistance in background field**
 - **Soldering after HT → low resistance in background field**
- **Option to be used in R2D2:**
 - **Detailed design and mockups required**



¹M. Kumar et al. “Preliminary Tests of Soldered and Diffusion-Bonded Splices Between Nb3Sn Rutherford Cables for Graded High-Field Accelerator Magnets”, IEEE TAS, 2019

- **Issue: 650°C heat treatment (HT) required for Nb₃Sn**
- **Goal: observe and quantify dimensional changes**
 1. Understand thermo-mechanical behaviors
 2. Predict and minimize stress in coils after fabrication
 3. Optimize performances of Nb₃Sn magnets
- CEA/CERN collaboration:
 - Longitudinal contraction on small coils after HT^{1,2}
 - **Representative of series production for HL-LHC at CERN**



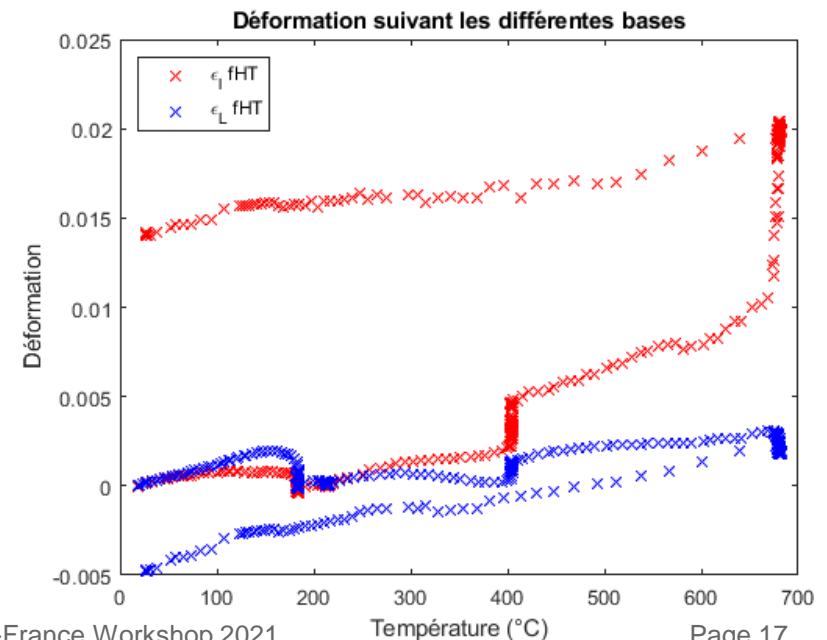
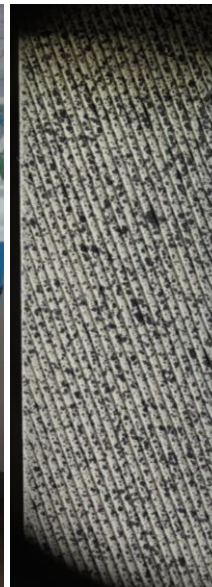
¹M. Durante et al.,
IEEE TAS, 2016
²E. Rochepault et al.,
IEEE TAS, 2016

Courtesy M. Abdel Hafiz

- CEA Paris-Saclay /LMT-ENS Paris-Saclay collaboration:
- Innovative method using High-temperature Digital Image Correlation: **3-dimensional + Multi-scale + Adaptable to different samples (cables, coils...)**.
- **First observation of width change for a Nb₃Sn cable as a function of temperature^{1,2}**

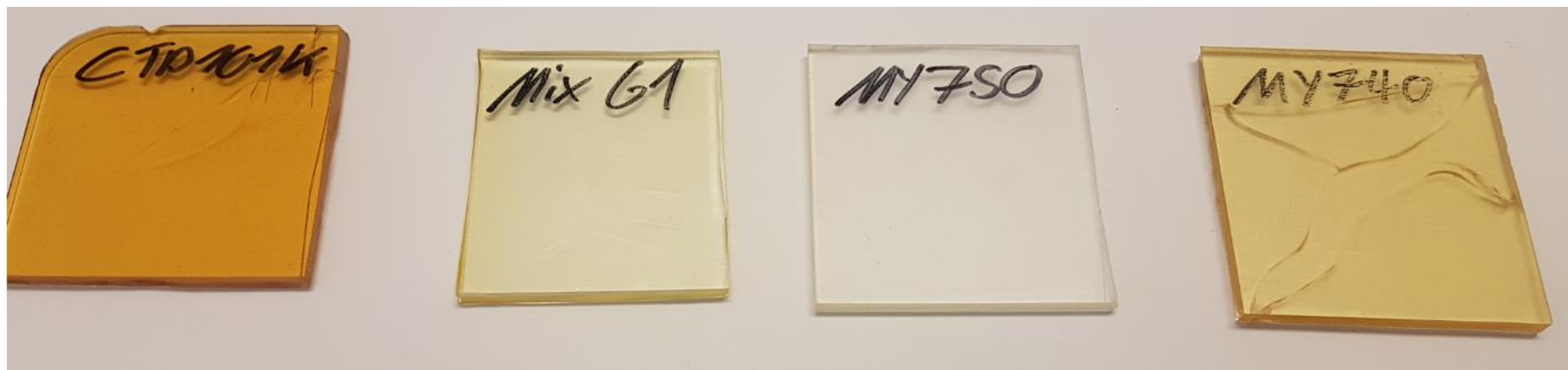
¹M. Abdel Hafiz, E. Rochepault et al., ASC2020

²M. Abdel Hafiz, PhD thesis



- ETH-Zurich/CERN/CEA collaboration:
→ Qualify different resin systems (ongoing)

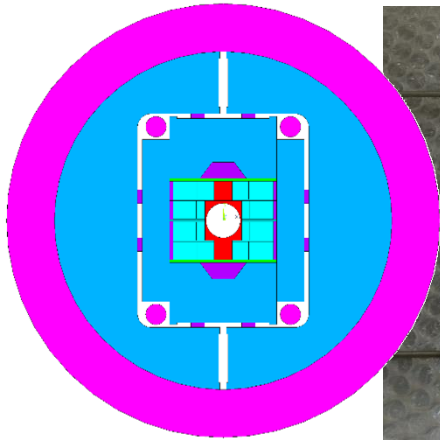
Courtesy A. Brem



- CEA internal R&D:
→ Study different interface combinations



Courtesy W. He,
F. Rondeaux



CEA internal R&D:

- **Develop new bladder manufacturers**
- **Validate strain gauge measurements at cold**
- Study material behavior at cold
- Develop new measuring methods



- **CEA/CERN strategy for FCC-hh 16T Magnets:**
 - **Quadrupole** conceptual design finalized
 - CEA/CERN **Dipole** Magnet strategy
 - Small Coil fabrication ongoing
 - 12 T R2D2 Demonstrator: detailed design ongoing
 - 16 T F2D2 Demonstrator: conceptual design proposed

- **CEA carrying parallel R&D programs:**
 - Winding → **grading**
 - Junctions → **grading**
 - Thermo-mechanics during HT → **Nb₃Sn performances**
 - Electrical insulation → **high voltages**
 - Mechanical structures → **high stresses**

- **CEA involved in many collaborations, for instance:**
 - **European institutes** : CERN, EPFL-SPC, ETHZ...
 - **French universities** : LMT-ENS Paris-Saclay